

Low-frequency vacuum squeezing via polarization self-rotation in Rb vapor

Eugeny E. Mikhailov and Irina Novikova

The College of William & Mary, Williamsburg, Virginia, 23187

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We observed squeezed vacuum light at 795 nm in ^{87}Rb vapor via resonant polarization self-rotation, and report noise sidebands suppression of ≈ 1 dB below shot noise level spanning from acoustic (30 kHz) to MHz frequencies. This is the first demonstration of sub-MHz quadrature vacuum squeezing in atomic systems. The spectral range of observed squeezing matches well typical bandwidths of electromagnetically induced transparency (EIT) resonances, making this simple technique for generation of optical fields with non-classical statistics at atomic transitions wavelengths attractive for EIT-based quantum information protocols applications.

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The reliable and efficient generation of an electromagnetic field with non-classical statistics (i.e. “squeezed” light, or “squeezed” vacuum) is important for a number of applications from precision metrology to quantum information. Many recently proposed protocols for controlling and manipulating quantum states of light rely on the resonant coherent interaction of light with atomic ensembles [1, 2]. These applications require sources of light with controllable quantum mechanical properties in a characteristic bandwidth that is resonant with atomic transitions. Electromagnetically induced transparency (EIT) resonances, for example, are widely used in slow light and quantum memory experiments [3, 4], few photon wave-packet generation and control [5, 6, 7, 8], etc. Their typical bandwidths range from a few tens of Hz to a few MHz [1].

At present optical parametric oscillators (OPO) operating below threshold offer the best performance for squeezed vacuum generation [9]. Many EIT experiments are based on Rb D_1 line (795nm) transitions, and OPO performance is limited at this wavelength due to increased material absorption for 397 nm near-ultraviolet up-converted pump field, as well as various photothermal effects arising at higher pump power [10]. Another challenge is to produce low-frequency squeezing to match the characteristic bandwidth of EIT resonances. While the generation of squeezed light with sub-MHz sideband frequencies is theoretically possible [11], practically it becomes a very challenging and resource-consuming task due to significant experimental complexity. Nevertheless, impressive progress in generation of low-frequency squeezed vacuum at Rb resonance wavelength has been recently reported [10], and such sources were used to demonstrate slow light and reversible mapping of squeezed vacuum states via EIT in Rb [12, 13, 14].

The generation of resonant squeezed vacuum based on the nonlinear interaction of light with atoms offers a simpler alternative to traditional nonlinear crystal-based squeezers, and various techniques have been explored re-

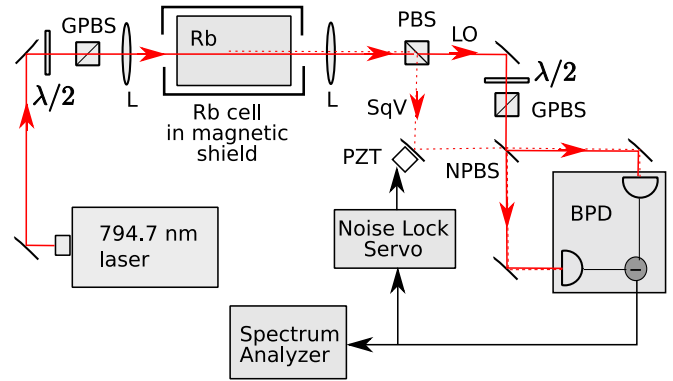


Fig. 1. Schematic of the experimental setup. SqV is squeezed vacuum field, LO is local oscillator. Please see the text for other abbreviations.

cently (see review in [15]). This Letter reports successful observation of low-frequency squeezed vacuum at the Rb optical D_1 transition (795 nm) based on nonlinear polarization self-rotation effect, recently proposed by Matsko *et al.* [16]. Ries *et al.* reported the proof-of-principle demonstration on Rb D_2 line [17], although some later experiments failed to reproduce this result [18]. The present experiment is aimed to resolve this controversy.

The polarization self-rotation effect describes the rotation of polarization direction of elliptically polarized light as it propagates through a medium, and it occurs in many optical substances. The effect is characterized by a self-rotation parameter g , such that $\phi_{SR} = g\varepsilon L$, where ϕ_{SR} is the polarization rotation angle of the input field with ellipticity ε after traversing optical medium of length L . In resonant atomic vapor self-rotation occurs due to unbalanced ac-Stark shifts caused by unequal intensities of circularly polarized components of the input light field [19, 20]. In case of linearly polarized pump field there is no macroscopic polarization ro-

tation, but same mechanism couples quantum noise in two initially independent circular components, and thus produces cross-phase modulation between classical linearly polarized pump field and vacuum field in the orthogonal polarization. As a result, quadrature squeezing of the vacuum field occurs [16]. The expected noise suppression below standard quantum limit is proportional to $1/(gL)^2$, but is reduced by optical losses in the system. In practice, the observation of maximum squeezing requires the optimization of many experimental parameters such as laser detuning and power, atomic density, etc. Spontaneous emission noise in thermal vapor may also reduce or destroy squeezing by introducing extra noise [15, 18]. We also observed that squeezing generation is sensitive to the presence of uncompensated magnetic field inside the cell.

The schematic of the experiment is shown in Fig. 1. The experimental settings are very simple with no need for expensive equipment, such as powerful lasers or high-quality optical cavity, and the resulting non-classical field is automatically generated at near-resonant wavelength. An external cavity diode laser (≈ 7 mW total power) was tuned to the Rb D_1 line $5^2S_{1/2} \rightarrow 5^2P_{1/2}$ ($\lambda \approx 795$ nm). The laser beam was focused with a pair of lenses (L) inside a cylindrical glass cell, containing isotopically enriched ^{87}Rb and 2.5 Torr of Ne buffer gas, and the estimated minimum laser beam diameter inside the cell was 0.175 ± 0.015 mm FWHM. The cell length and diameter were 75 mm and 22 mm consecutively, and the cell windows were tilted at about 10° to prevent backward reflections. The cell was mounted inside a three-layer magnetic shielding to minimize stray magnetic fields. The cell was maintained at 66°C . Before entering the cell the laser beam passed through a high quality Glan polarizing beam splitter (GPBS) to purify its linear polarization. A half-wave plate ($\lambda/2$) placed before the input polarization beam splitter allowed for smooth adjustments of the pump field intensity.

After the cell the electromagnetic field in orthogonal polarization (squeezed vacuum field, SqV) was separated on a polarization beam splitter (PBS), and its noise properties were analyzed using a homodyne detection. The original pump field played the role of a local oscillator (LO), that was attenuated and brought to the same polarization as the vacuum field using another GPBS and a half-wave plate combo. Phase difference between the local oscillator and the vacuum field was controlled by a mirror placed or a piezo-ceramic transducer (PZT) that allowed changing the differential pathlength between two arms. We then mixed these two fields at a 50/50 non-polarizing beam splitter (NPBS), and directed two beams to a home-made balance photodetector (BPD) with a gain of 10^4 V/A, 1 MHz 3 dB bandwidth and electronic noise floor located at 6 dB below shot noise at low frequencies. Two matched Hamamatsu S5106 photodiodes with quantum efficiency $\eta = 87\%$ and a low noise high bandwidth TI OPA842 operational amplifier were crucial components of the BPD. For our measurement we

locked the relative phase in BPD detection scheme to minimum value of quadrature noise in SqV channel by using a noise-locking technique [21]. The output of BPD was bandpass filtered with a central frequency 1.2 MHz and a RBW 100 kHz and then sent to an envelope detector with VBW=30Hz, while dithering the LO phase with a 1 kHz modulation frequency. A demodulation of the output of the envelope detector with a lock-in amplifier provided correction signal for a servo.

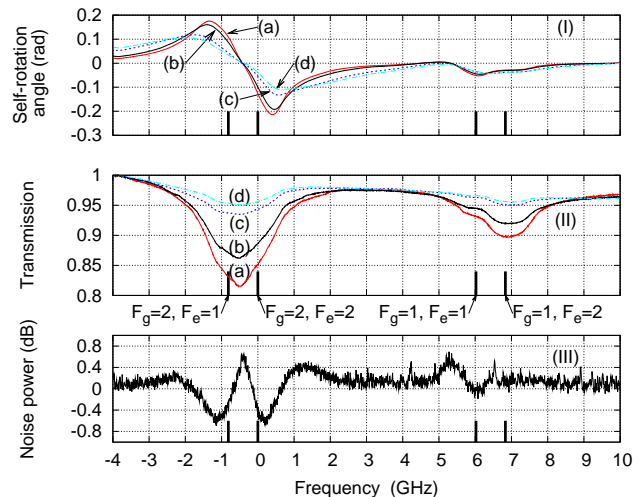


Fig. 2. Polarization self-rotation angle (ϕ_{SR}) (I) and transmission (II) in the ^{87}Rb cell for the light field with $\varepsilon = 4^\circ$ ellipticity. Laser powers are 1.04 mW (a), 1.54 mW (b), 4.15 mW (c), and 6.37 mW (d). (III) Minimum quadrature noise in orthogonal polarization at 1200 MHz central frequency, for linearly polarized pump field with power 6.58 mW. Zero laser detuning corresponds to $F_g = 2 \rightarrow F_e = 2$ ^{87}Rb transition.

Fig.2 (I,II) shows the self-rotation and absorption of the pump field when a small ellipticity $\varepsilon = 4^\circ$ was introduced by a quarter-wave plate placed before the cell (we define ε as an angle between $\lambda/4$ plate fast axis and pump field polarization direction). Maximum self-rotation was observed near both $F_g = 2 \rightarrow F_e = 1, 2$ transitions of ^{87}Rb , although the polarization ellipse rotated in opposite directions. Increasing the laser power resulted in increased transparency of the atomic vapor due to more effective optical pumping of atoms into non-interacting combination of Zeeman sublevels of $F_g = 2$ state as well as to off-resonant $F_g = 1$ state. The second mechanism was most likely also responsible for some reduction in the self-rotation.

Fig.2 (III) shows a sample spectrum of minimum (squeezed) quadrature of the optical field of orthogonal polarization in case of linearly polarized pump field (*i.e.* no measurable polarization self-rotation occurs). The positions of squeezing peaks correspond roughly to those of self-rotation. A maximum squeezing of 0.6 dB was detected at detunings of about 100 MHz to the red from $F_g = 2 \rightarrow F_e = 1$ as well as about 100 MHz to the blue

from $F_g = 2 \rightarrow F_e = 2$, and excess noise was observed in the region between two transitions. We also observed minute amount of squeezing near $F_g = 1 \rightarrow F_e = 1$ transition. Vacuum squeezing showed similar dependence of the optical frequency for different pump powers.

At the same time the squeezed quantum noise frequency spectrum showed rather strong variation with the pump field power, as Fig. 3(I) demonstrates. The detected squeezing was uniformly low at low laser powers > 1 mW. As the pump power increased, we first observed maximum squeezing in the low-frequency part of the quantum noise spectrum. Then broadband squeezing kept increasing at the expense of low-frequency components and reached its maximum at about 4 mW. Further power increase began slowly degrading observed squeezing. Such a low value of optimal laser power may in principle explain why squeezing was not observed in the experiments of Hsu *et al.*, where much higher laser powers (35 mW) were used [18].

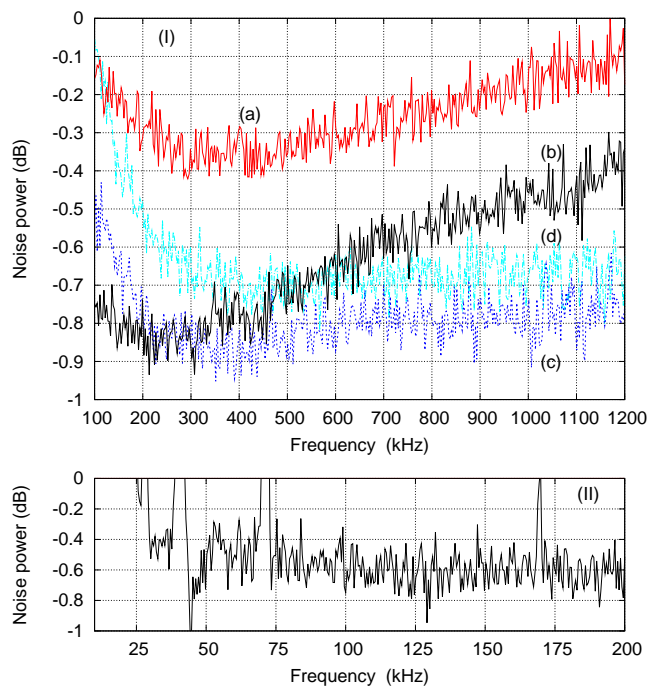


Fig. 3. (I) Squeezed quadrature noise vs sideband frequency for different laser power settings. Laser powers are 1.04 mW (a), 1.54 mW (b), 4.15 mW (c), and 6.58 mW (d). (II) Low-frequency component of squeezed quadrature noise spectrum for the laser power 1.54 mW. Shot noise corresponds to 0 dB. The laser is tuned to the maximum squeezing near 100 MHz detuning.

To investigate the low-frequency part of the squeezing spectrum in more detail, we studied the case of 1.54 mW pump power more carefully. Fig. 3(II) demonstrates that broadband low frequency squeezing was generated at sideband frequencies as low as 30 kHz. A few extra noise peaks at 40 and 70 kHz were most likely due to backscattering of the pump field into the system.

In conclusion, we successfully demonstrated generation of low-noise broadband squeezing via self-rotation effect in ^{87}Rb at 795 nm, independently confirming previous proof-of-principle experiments of Ries *et al.* [17]. The maximal measured squeezing value is 0.87 ± 0.02 dB at 400 kHz, and the squeezing was detected in the range of sideband frequencies from 30 kHz to 1.2 MHz. Up to our best knowledge, this is the first demonstration of a sub-MHz quadrature-squeezed vacuum in atomic systems. Further improvements are possible with optimization of the system (*i.e.* by optimizing the buffer gas pressure and composition, pump field parameters, etc.). Supporting detail theoretical analysis is in progress. Such low-cost method for generation of low-frequency non-classical fields near atomic optical resonances may be useful and attractive for various quantum memory tests and applications.

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